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Climate change and northern prairie wetlands: Simulations of long-term dynamics

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Abstract

A mathematical model (WETSIM 2.0) was used to simulate wetland hydrology and vegetation dynamics over a 32-yr period (1961–1992) in a North Dakota prairie wetland. A hydrology component of the model calculated changes in water storage based on precipitation, evapotranspiration, snowpack, surface runoff, and subsurface inflow. A spatially explicit vegetation component in the model calculated changes in distribution of vegetative cover and open water, depending on water depth, seasonality, and existing type of vegetation.

The model reproduced four known dry periods and one extremely wet period during the three decades. One simulated dry period in the early 1980s did not actually occur. Simulated water levels compared favorably with continuous observed water levels outside the calibration period (1990–1992). Changes in vegetative cover were realistic except for years when simulated water levels were significantly different than actual levels. These generally positive results support the use of the model for exploring the effects of possible climate changes on wetland resources.

Simulation models are used extensively to evaluate the potential effects of changing climate on the earth's natural systems (e.g. Houghton et al. 1990; Chang et al. 1992; Parton et al. 1994; Sulzman et al. 1995). General circulation models (GCMs) provide projections of changes in temperature, precipitation, and other climate variables as a result of increased concentrations of atmospheric greenhouse gases (e.g. Schneider 1987; Schlesinger 1991). Assessment of impacts to ecosystems also depends heavily on the use of simulation models because ecosystem-scale experiments are difficult and costly to conduct in the field or laboratory (DeAngelis and Cushman 1990; Burke et al. 1991; Malanson 1993).

Developing and testing simulation models using present climate conditions frequently are first steps in assessing the effects of climate change (Power 1993). Unfortunately, these steps often are limited by lack of long-term data, leading to models that are not tested using a wide range of climatic conditions. For example, models developed using average years may produce unrealistic results when the model is applied to extreme conditions. Use of extreme years in model calibration is more desirable, yet may not reproduce average conditions. Ideally, model development and testing should include minimum, maximum, and average climatic conditions, particularly for systems that occur in highly variable climates.

The relatively small, shallow-basin wetlands located throughout the glaciated Great Plains region of the north-central United States and south-central Canada occur in such a highly variable climate. Wetland water levels and vegetation fluctuate widely in response to seasonal and annual wet and dry periods, which are characteristic of the region (Borchert 1950; Kantrud et al. 1989). Conditions in semipermanent wetlands (i.e. wetlands that hold water throughout the growing season during most years) (Stewart and Kantrud 1971) range from dense emergent cover during prolonged drought, to large areas of open water in wet years, to more balanced ratios of vegetation to open water during average years (van der Valk and Davis 1978; van der Valk 1981; Kantrud et al. 1989).

Few studies have examined the potential impacts of climate change on prairie wetlands. Most research on

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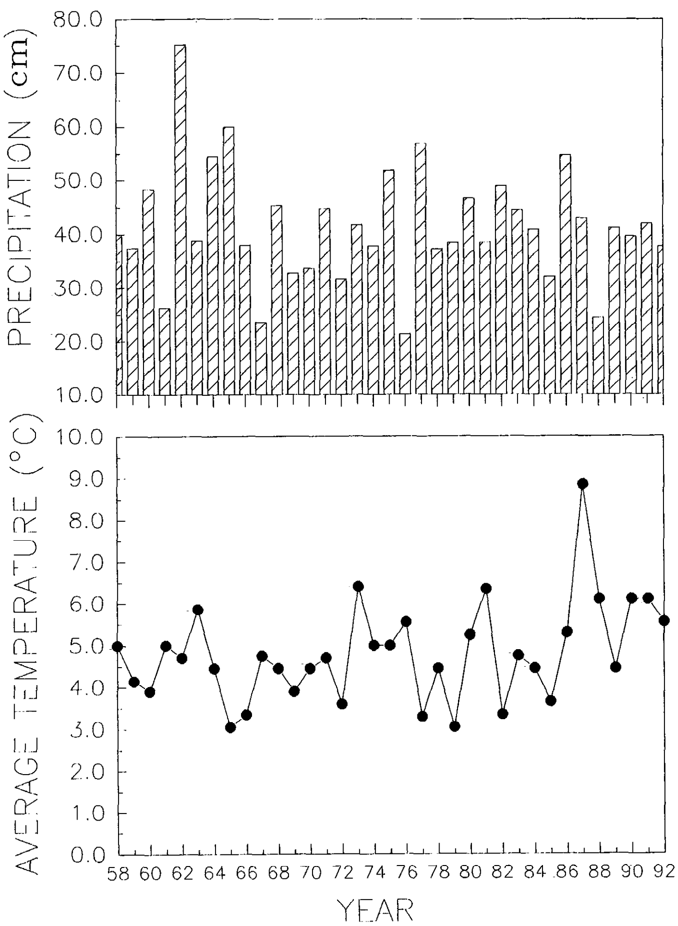


Fig. 1. Average yearly temperature (Pettibone, North Dakota) and total yearly precipitation (Woodworth, North Dakota) for 1958–1992.

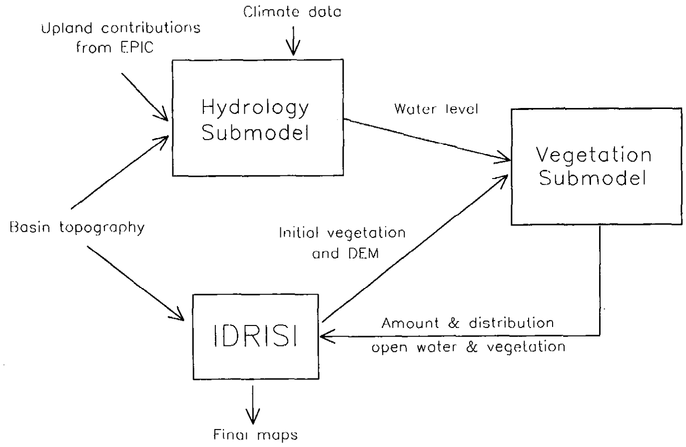


Fig. 2. Flowchart of overall prairie wetland model, WETSIM 2.0. (IDRISI is a pc-based GIS software package: Eastman 1992).

these ecosystems has characterized current wetland hydrology and vegetation dynamics (e.g. Shjeflo 1968; LaBaugh et al. 1987, 1996; Kantrud et al. 1989; Winter 1989; Woo and Rowsell 1993; Woo and Winter 1993; Winter and Rosenberry 1995). Crowe (1993) used a coupled water balance-salinity model to examine sensitivity to climatic variability of a large lake dominated by groundwater. Hondzo and Stefan (1993) used a lake-water quality model linked to a daily weather database to simulate water temperature profiles under changing climate conditions in Minnesota lakes. Several field experiments in northern Alberta have examined effects of fire and drought on wetland vegetation, including implications for potential climate change (Hogenbirk and Wein 1991, 1992). Larson (1994) reviewed issues related to climate change and waterfowl habitat in the northern Great Plains, particularly in regard to multiple simultaneous factors (i.e. temperature, precipitation, CO_2, UV radiation).

Two of us have developed, tested, and applied to climate-change impact analyses a simulation model of the hydrology and vegetation dynamics in semipermanent prairie wetlands (Poiani and Johnson 1991, 1993*a*,*b*; Poiani et al. 1995). The model was developed using 11 yr of data (1979–1989) from wetland P1 located on the Cottonwood Lake study site, North Dakota (LaBaugh et al. 1987). The model was tested using data from a nearby basin. Results showed that a relatively simple spatially explicit model accurately simulated water level and vegetation dynamics for the decade; the study also highlighted several components of the model that needed improvement (Poiani and Johnson 1993*a*). Several of these studies also examined the potential effects of a changing climate on wetland response using hypothetical temperature and precipitation changes and output from a GCM (Poiani and Johnson 1991, 1993*b*; Poiani et al. 1995).

Based on results of initial studies, we significantly changed the original model version (referred to as "original" throughout this paper) (Poiani and Johnson 1993*a*). Site-specific empirical relationships for surface runoff, seepage inflow, and spring refill caused by snowmelt were replaced by more general, physically based calculations. We improved evapotranspiration calculations and the seed-germination component and added stochasticity to vegetation dynamics. In addition, we greatly extended the model testing period from one decade (which did not include a full range of current climatic conditions) to three decades (1961–1992) that encompassed greater weather extremes (LaBaugh et al. 1996), such as the wet years of 1962, 1964, and 1965 and the dry years of 1961, 1967, 1976, and 1988 (Fig. 1).

This paper has several objectives: to describe version two of the wetland simulation model (WETSIM 2.0 for WETland SIMulator), to present results from long-term simulations for wetland P1 using WETSIM 2.0, and to assess the potential of the model to examine the effects of future climate change on prairie wetlands.

Wetland model

WETSIM 2.0 consists of two interacting components: hydrology and vegetation submodels (Fig. 2). The submodels calculate monthly water level and the amount and distribution of vegetation cover. The vegetation submodel interfaces with a raster-based geographic information system (GIS) (Eastman 1992) that processes input data and displays and analyzes submodel output (Fig. 2).

Hydrology submodel—The hydrology submodel in WETSIM 2.0 consists of a water-budget accounting procedure (Fig. 3). A starting water level is assigned for the first month of the simulation period and the submodel converts this elevation to water volume given a stage-volume relationship for the wetland basin. Subsequent water volumes are calculated monthly and converted back to water surface elevation for output to the spatially explicit vegetation submodel (Fig. 2). Water elevation cannot fall below the wetland bottom [i.e. when the entire wetland is dry; 557.7 m above sea level (m asl) for wetland P1].

The water budget equation for the hydrology submodel is (Fig. 3)

$$\text{vol}_T = \text{vol}_{T-1} + p_w + m_u + so_u + ss_u - ET_w.$$

T is time, vol is volume, p_w is rain and snow falling directly on the wetland, m_u is upland snowpack at melting, so_u is surface runoff from the contributing watershed, ss_u is subsurface inflow from the contributing watershed (i.e. net seepage input), and ET_w is evapotranspiration from the wetland. All values are in cubic meters except T, which is in months. Long-term monitoring indicates that seepage outflow is common but is a relatively minor component of the water budget of wetland P1 (Winter and Rosenberry 1995). Due to its intermediate position in the local groundwater flow system, P1 typically receives groundwater discharge, but reversals of flow caused by evapotranspiration do occur (LaBaugh et al. 1987; Winter and Rosenberry 1995).

In our applications, total monthly precipitation from the Cottonwood Lake site was used whenever possible. Data from the nearest weather station (Woodworth, North Dakota) were used for missing site records (i.e. primarily winter months and all data prior to 1979) (NOAA, National Climatic Data Center, Asheville, North Carolina). Monthly values of precipitation in centimeters were converted to volume by multiplying by the area of the wetland basin (22,260 m^2 for wetland P1).

Evapotranspiration from the wetland was equal to potential evapotranspiration (potET) calculated with the Blaney-Criddle method. This commonly used method in semiarid climates is based on day length, average monthly temperature, and a monthly "crop" coefficient (U.S. Dep. Agric. 1972):

$$\text{potET} = [(0.0173 \times Ta - 0.314) \times kc \times Ta \times (\text{dl}/4{,}463)] \times \text{No. d.}$$

pot ET is in inches (1 in = 2.54 cm), Ta is average monthly temperature in °F [(°F − 32) × 5/9 = °C], kc is crop growth stage coefficient, dl is number of daylight hours, and No. d is number of days in a month. The constant 4,463 is the total number of daylight hours for 1 yr at the latitude of the study wetland (47°N). When average monthly temperature was less than 1.7°C (35°F), the first term in parentheses (i.e. $0.0173 \times Ta - 0.314$) was given a constant value of 0.3 (U.S. Dep. Agric. 1972). Monthly values of evapotranspiration in inches were converted to centimeters and then to volume by multiplying by the area of the wetland basin.

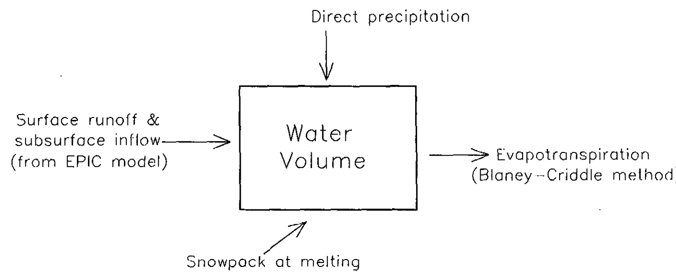


Fig. 3. Flowchart of hydrology submodel in WETSIM 2.0.

Precipitation accumulated as snow if the average monthly air temperature was <0°C. We assumed that the recorded snowfall was uniformly distributed throughout the contributing watershed. Losses from the upland snowpack (and from snow falling directly on the wetland) due to sublimation and evaporation occurred as a function of evapotranspiration rate (loss = pot ET × 0.87; coefficient related to the latent heat of fusion) (W. Parton pers. comm.). Water contributions from snowpack in the contributing watershed were added once a year to the wetland water budget (1st month when temperature >0°C) because the relatively shallow snowpack in the region typically melts within several days or weeks (Shjeflo 1968; Woo and Rowsell 1993; Woo and Winter 1993). Snowpack (in cm) was converted to water volume by multiplying by the area of the contributing watershed (170,291 m^2 for wetland P1; excluding area of basin) and was added to wetland water volume for that month.

Surface runoff and subsurface inflow to the wetland from the contributing watershed were calculated using the erosion productivity impact calculator (EPIC) model. EPIC is a simulation model developed to assess the relationship between soil erosion and soil productivity throughout the U.S. (Sharply and Williams 1990; Williams et al. 1990) and can be used to determine the effect of management practices on agricultural production and soil and water resources.

The EPIC model contains a complex hydrology component that simulates water movement through a soil profile of up to 10 layers. EPIC first calculates surface runoff for each daily rainfall using the Soil Conservation Service (SCS) curve number procedure (Sharply and Williams 1990). Precipitation remaining after runoff enters the soil profile. Flow from one soil layer to a lower layer occurs when soil water content exceeds field capacity, and excess water drains from the layer until storage returns to field capacity. In this way, EPIC calculates daily values of surface runoff, downward percolation, and lateral flow for a given soil profile based on its physical properties (e.g. field and wilting capacity, bulk density, hydraulic conductivity, average slope). In the wetland model, we assigned a portion of downward percolation and lateral flow from the contributing watershed as net seepage inflow to the basin. The amount of EPIC-generated subsurface flow added to the wetland (13%) was determined

Table 1. Cover types and adjusted water depth ranges used in the vegetation submodel. Original water depth ranges are given by Poiani and Johnson (1993*a*).

Cover type	Possible water depths
Upland	<-70 cm*
Meadow-shallow marsh emergent	Primarily -70 to -6 cm; occasionally <-70 cm
Deep marsh emergent	Primarily -5 to 45 cm
Open water	Primarily >45 cm; occasionally 6–45 cm
Seedlings	<-70 to 3 cm
Mixed plants	<-70 to 3 cm
Mixed emergents	-70 to 45 cm
Exposed soil	<-70 to 3 cm

* Negative water depths occur when a cell surface elevation is greater than the water elevation and indicate an approximate depth to the water table.

by calibration with observed data and is discussed in more detail later.

Estimates of surface runoff, percolation, and lateral flow were derived externally using the EPIC model. Daily values were summed by month, reformatted, and passed to the wetland hydrology submodel via a specified input file. Soil input parameters for EPIC were taken from site-specific soils data whenever possible (J. Arndt pers. comm.) and supplemented by SCS soil surveys. Soil parameters, particularly those from SCS soil surveys, were highly generalized, representing average conditions for a soil series over a large region. This was acceptable for the purposes of the wetland model because we wanted to represent one "typical" upland soil profile adjacent to the wetland. Climatic data needed for EPIC are daily minimum and maximum temperature (from Pettibone, North Dakota) and daily precipitation (Cottonwood Lake site and Woodworth, North Dakota). Surface runoff and subsurface inflow (in mm) were converted to volume by multiplying by the area of the contributing watershed.

Vegetation submodel—The vegetation submodel in WETSIM 2.0 calculates the amount and spatial distribution of vegetation cover and open water in the wetland. Within the submodel, the wetland basin and upland margin are represented by a grid with uniform cells. Cell size is determined according to wetland size and appropriate scale for vegetation processes. We used a cell size of 9.3 m^2 for a total of 5,037 cells. Continuous topographic characteristics of the basin (i.e. digital elevation model) were derived in the GIS by interpolating surveyed point elevations. Basin topography from the GIS and whole-basin water levels generated by the hydrology submodel were provided to the vegetation component (Fig. 2), and cell water depth was calculated monthly (water depth = water elevation − surface elevation). "Negative water depths" indicate an approximate depth to water table for higher elevation cells.

An initial cover-type grid, compiled in the GIS, also was input to the vegetation submodel and thereafter updated monthly during the growing season (May–October). Changes in cover types occurred when a series of criteria were met. Criteria were a function of existing cover type, previous and current water depths, time period in a given water depth range, location of cell, and seasonality (Table 1) (Poiani and Johnson 1993*a*). The current version of the submodel has eight cover types (upland, meadow-shallow marsh, deep marsh, open water, seedlings, mixed plants, mixed emergents, and exposed soil). Four cover types represent relatively permanent zones, including upland vegetation, combined meadow-shallow marsh emergents (e.g. *Carex* spp., *Scolochloa festucacea*), deep marsh emergents (e.g. *Typha* spp., *Scirpus* spp.), and open water. These four types loosely correspond to a specific range of water depths (Table 1). The other four represent more transient cover types present during the dry phase of the cover cycle (Table 1) and include exposed soil, seedlings, mixed species of drawdown plants (mixed plants), and mixed species of shallow and deep marsh emergents (mixed emergents). Outputs from the vegetation submodel are GIS images and statistical files with monthly and yearly cover type amounts and distributions.

Methods

Model data and calibration—The Cottonwood Lake site is in Stutsman County (south-central North Dakota) and is comprised of a complex of seasonal and semipermanent wetlands currently surrounded by ungrazed grassland. The site has one of the longest and most extensive data records for shallow-basin prairie wetlands in the Great Plains region. Data used in this study for model calibration and testing were from semipermanent wetland P1, classified as slightly brackish (i.e. specific conductance = 500–2,000 $\mu S\ cm^{-1}$) (Stewart and Kantrud 1971). Continuous water levels were available for wetland P1 from 1979 to 1992, as well as aerial photographs of wetland vegetation and open-water distributions for each year (LaBaugh et al. 1987; LaBaugh and Swanson 1992; Poiani and Johnson 1993*a*). Further description of wetland P1 and the Cottonwood Lake site are given elsewhere (Winter and Carr 1980; LaBaugh et al. 1987, 1996; Swanson 1987*a,b*; Poiani and Johnson 1988, 1989, 1993*a*; LaBaugh and Swanson 1992; Arndt and Richardson 1993; Winter and Rosenberry 1995).

Calibration simulations for WETSIM 2.0 performed in this study used data from the period 1979–1989, with initial conditions from 1979. For hydrology calibration simulations, spring water level was reset to observed values each year so several growing season parameters could be adjusted independently (e.g. EPIC-generated subsurface inflow). In addition, continuous simulations where spring refill was calculated were used to adjust winter snowpack and spring refill components. We then compared submodel output to observed changes for 1979–1989 and adjusted model coefficients and parameters as discussed below to produce the best fit between simulated and observed values. Vegetation parameters were calibrated similarly, including the use of results from original submodel tests published previously (Poiani and Johnson 1993*a*).

Calibrated parameters in the hydrology submodel of WETSIM 2.0 included monthly values of the Blaney-Criddle crop growth coefficient (*kc*), and the portion of EPIC-generated subsurface flow input to the wetland. Monthly values of *kc* during the growing season were increased from original values recommended for alfalfa so they more accurately represented higher water losses from emergent wetland vegetation. Adjustment of evapotranspiration rates from upland snowpack (i.e. decreased *kc* and pot ET values in winter months) also was necessary to refine spring refill in the hydrology submodel. Thirteen percent of EPIC-generated percolation and lateral flow was added to the wetland water budget to best match observed water level changes. Calibrated parameters in the vegetation submodel of WETSIM 2.0 included boundaries of water-depth categories, length of time in a water-depth category, percent seed germination by month, and stochasticity factors in emergent vegetation mortality by flooding and establishment of upland, meadow-shallow marsh, and deep marsh types. Boundaries of and length of time in water-depth categories initially were the same as in the original submodel version (Poiani and Johnson 1993*a*).

Long-term simulation—Following calibration, a long-term simulation spanning more than three decades (1961–1992) was conducted to evaluate model performance. This period was chosen because some observations of water level and vegetation were available for wetland P1 prior to 1979, and 3 yr of continuous data were available after 1989. Ground photographs, occasional aerial photographs, and estimates of water level were made for earlier years (Swanson 1987*a,b,* 1992, unpubl. data). Continuous water levels and yearly vegetation data for wetland P1 outside the calibration period included 1990–1992.

We used initial water levels and general vegetation that reflected conditions prior to 1961. Water levels at the site were known to be extremely high in 1957 and all of the wetlands were dominated by open water (G. Swanson unpubl. data). Precipitation during 1958–1960 was average (Fig. 1), and water levels and cover ratios probably were stable. In addition, several larger semipermanent basins near the site contained from 0.5 to 1.0 m of water in May 1961 (Shjeflo 1968; Eisenlohr et al. 1972). Thus, initial water elevation for wetland P1 was set at 558.00 m asl, which resulted in water depths no deeper than 30 cm throughout the basin. The initial ratio of emergent cover to open water was set at 50 : 50. A 32-yr simulation was run using initial conditions and calibrated parameters as described above. The vegetation submodel performed poorly in this initial run. Original boundaries of water-depth categories between cover types (calibrated using data from 1979 to 1989) were too high, and changes in emergent cover were unrealistic. Water-depth boundaries were readjusted and only results from this adjusted simulation are presented ("simulated" in tables and figures). Water-depth boundaries were the only parameters readjusted in either submodel following initial calibration.

After readjusting vegetation parameters, we performed a series of sensitivity simulations. This analysis did not represent a full, systematic sensitivity analysis, nor did it represent a climate-impact study. Sensitivity results were provided to illustrate system response to changes in several important calibrated parameters and initial conditions, especially because such values were uncertain or could be affected by future climate change. Four parameters in the "base" hydrology submodel were varied: ± 0.10 units of calibrated monthly winter-spring (November–April) Blaney-Criddle crop coefficients (e.g. $0.78 = 0.88$ and 0.68); ± 0.10 units of calibrated monthly growing-season Blaney-Criddle crop coefficients (May–October); $\pm 20\%$ of the 13% calibrated subsurface inflow to the wetland (i.e. 15.6 and 10.4%); and +130-cm and −30-cm initial water elevation (highest observed and completely dry). Adjustments for crop coefficients and seepage inflow (± 0.10 units and $\pm 20\%$) were determined subjectively after examination of model sensitivity during parameter calibration (± 0.10 units for crop coefficients is equal to $\pm 10\%$ when $kc = 1.00$).

Limitations in stage-volume data for wetland P1 precluded conversions of water volume $>40{,}800$ m^3 to accurate values of water elevation. Thus, results from all simulations are presented in terms of wetland water volume rather than water elevation because water volume in some years of the simulations exceeded the value 40,800 m^3. Simulation results were compared to observed data or to each other using descriptive statistics. The deterministic nature of the hydrology submodel together with the discontinuous and qualitative aspects of observed data prior to 1979 precluded tests of statistical significance.

Results

Hydrology—The hydrology submodel depicted known wet-dry cycles over the three decades (Fig. 4). The wettest period observed for wetland P1 (1966–1970) was simulated accurately by the submodel (Fig. 4). For the most part, water volumes during normal rainfall years were simulated accurately, including 1975, 1979–1980, and 1983–1986 (Fig. 4). Water volumes in 1981–1982 and 1987 were underestimated by the submodel.

Drought periods also were simulated relatively well. Four known low-water periods were reproduced: 1961, 1973–1974, 1976–1977, and 1988–1992 (Fig. 4, Table 2). Drawdown was remarkably accurate for some of these periods. Simulated drying often occurred in the same month as observed (Fig. 4). One simulated dry period (1981–1982) did not actually occur and one simulated dry period was drier than observed (1972–1973). Although P1 did have a partial drawdown late in the growing season in 1973, the submodel depicted the dry period beginning in late 1972 and continuing in 1973 as more severe than observed (Table 2, Fig. 4). Actual water volumes in 1981 were relatively low but did not decline as

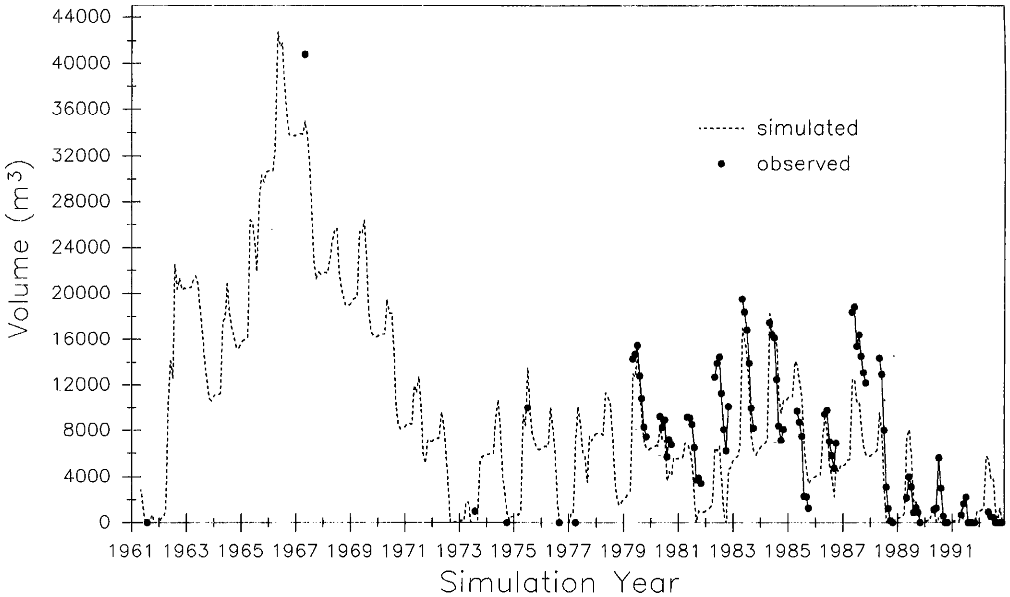


Fig. 4. Observed water volume in wetland P1 vs. model calculations, 1961–1992.

Table 2. Observed vs. simulated wetland dynamics (1961–1992).

	Water levels*		Water condition†		Vegetation dynamics‡	
Year	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
1961	ex low	ex low	comp. dd	comp. dd	1	1
1962–65	some high	some high	stable	stable	2	2
1966–70	ex high	ex high	stable	stable	2	2
1971	mod	mod	stable	stable	2	2
1972	mod	low	stable	comp. dd	2	3
1973	low	ex low	part. dd	comp. dd	3	1
1974	low	low	comp. dd	part. dd	3	3
1975	mod	mod	stable	stable	2	2
1976	low	low	comp. dd	comp. dd	3	3
1977	ex low	some low	comp. dd	stable	1	2
1978	mod	some low	stable	stable	4	2
1979	mod	mod	stable	stable	4	2
1980	mod	mod	stable	stable	5	2
1981	some low	ex low	stable	comp. dd	2	3
1982	mod	ex low	stable	comp. dd	2	3
1983	some high	mod	stable	stable	2	2
1984	some high	some high	stable	stable	2	2
1985	low	mod	part. dd	stable	3	2
1986	mod	mod	stable	stable	2	2
1987	some high	mod	stable	stable	2	2
1988–89	ex low	ex low	comp. dd	comp. dd	3	3
1990	ex low	ex low	comp. dd	comp. dd	3	1
1991	ex low	ex low	comp. dd	comp. dd	1	4
1992	ex low	ex low	comp. dd	comp. dd	4	4

* Ex low (high)—extremely low (high); mod—moderate; some low (high)—somewhat low (high).

† Comp. dd—complete drawdown; part. dd—partial drawdown.

‡ 1—Germination and establishment; 2—balanced ratio cover; 3—little or no germination; 4—mixed emergents central basin; 5—mixed emergents and open-water patches in central basin.

much as the submodel depicted (Fig. 4). Observed peak water volume in 1982 was ~7,800 m^3 greater than the simulated high water volume (~34 cm difference in water level).

Vegetation—Percent open water in the simulation with adjusted vegetation parameters rose to 61% by 1967 and remained over 50% until summer 1971. These patterns closely followed known changes in wetland P1 (Fig. 5A). Simulated cover ratios during normal rainfall years showed slightly less open water than observed conditions for the period of continuous data [e.g. 1984 = 39 : 61 observed vs. 23 : 76 simulated (open water : emergent cover), Fig. 5C; 1986 = 36 : 64 vs. 23 : 77; 1988 = 31 : 69 vs. 24 : 76]. This may have been due to lower-than-observed water level estimates in the hydrology submodel during 1981–1982 and 1987 (Table 2).

Simulated vegetation dynamics generally were realistic for drawdown periods except for those years when simulated water levels differed from actual levels by at least 10–20 cm. For example, P1 had low water and germination of mixed emergents in the central basin during spring 1977 (Table 2). Simulated water levels higher than observed in early 1977 (~15 cm) precluded establishment of mixed emergents during this period. The opposite problem occurred in 1973, when simulated water levels were lower than observed; the model showed germination when the wetland did not (Table 2). Other late-season complete or partial drawdowns were simulated correctly such as in 1974, 1976, and 1988 when water declined after August, little or no germination took place or, germination was restricted to a band inside the deep marsh zone and the central basin remained primarily as exposed mudflat (Table 2, Fig. 5B). Simulations showed early drawdown and significant germination in 1961, which was similar to observed conditions (Table 2).

Finally, the simulation model accurately represented vegetation dynamics during the prolonged drought of 1988–1992. Simulations showed late-season drawdown resulting in exposed soil with only scattered germination and establishment in the central basin in 1988–1989. Significant colonization of emergents occurred by 1990 in simulations and was observed 1 yr later in wetland P1 (Table 2).

Sensitivity—WETSIM 2.0 was somewhat sensitive to changes in amount of subsurface inflow from the contributing watershed (Table 3). An increase in subsurface inputs (from 13 to 15.6% of EPIC-generated inflows) produced a maximum water volume that was greater than that for the base run (base = 42,761 m^3; 15.6% inflow = 46,985 m^3). A corresponding decrease in subsurface inflow (10.4%) caused the wetland to dry out in 15 of 32 yr compared to 12 in 32 yr in the base simulation (Table 3).

The model also was sensitive to variation in calibrated Blaney-Criddle crop coefficients. Water level and cover ratios were particularly responsive to changes in growing season coefficients (Table 3). Higher coefficients (greater pot ET) increased the number of dry years, lowered maximum water volume, and produced slightly less maximum percent open water than in the base run (Table 3). Conversely, only three drawdown years occurred over the 32 yr when growing season coefficients were decreased, and maximum percent open water rose to 73 (compared to 61% base) (Table 3). Decreasing winter-spring coefficients (decreasing potET) also produced wetter conditions during the three decades with the wetland drying in only 7 yr out of 32 (12 of 32 base) (Table 3).

Model sensitivity to changes in initial water level lessened with time. The model also was more sensitive to higher initial water levels than to lower starting levels. For example, results from the −30-cm initial water-level simulation did not differ much from the base run; the number of dry years was 12 and the maximum percent open water was 61 for both (Table 3). An increase of 130 cm in initial water level, in contrast, caused greater water volume: 42,761 m^3 (base) vs. 69,805 m^3 (+130 cm). In addition, increased initial water level resulted in greater maximum percent open water: 61 (base) vs. 100 (+130 cm) (Table 3). By the late 1970s water volumes and cover ratios in this latter simulation compared more favorably with those from the base run (not shown).

Table 3. Sensitivity analysis for hydrologic submodel parameters. Simulations for period 1961–1992. *kc*—Blaney-Criddle crop growth coefficient; ss—subsurface inflow.

Simulation	Years dry*	Max water vol. (m^3)	Max % open water	Growth years†
Observed	11	40,800	>60	1961 1976–77 1991–92
Simulated (base)	12	42,761	61	1961 1973 1990–91
+0.10 units *kc* winter-spring	17	39,979	62	1961 1972–73 1990–91
−0.10 units *kc* winter-spring	7	45,544	64	1961 1973 1990–91
+0.10 units *kc* growing season	18	36,870	59	1961 1971–73 1988–91
−0.10 units *kc* growing season	3	48,745	73	1961
15.6% ss	11	46,985	66	1961 1973 1990–91
10.4% ss	15	38,537	61	1961 1972–73 1990–91
+130 cm initial water elevation	3	69,805	100	1990–91
−30 cm initial water elevation	12	42,761	61	1961 1973 1990–91

* Number of years wetland goes dry or nearly dry (n = 32) (<1,300 m^3).
† Years with significant plant growth in central basin.

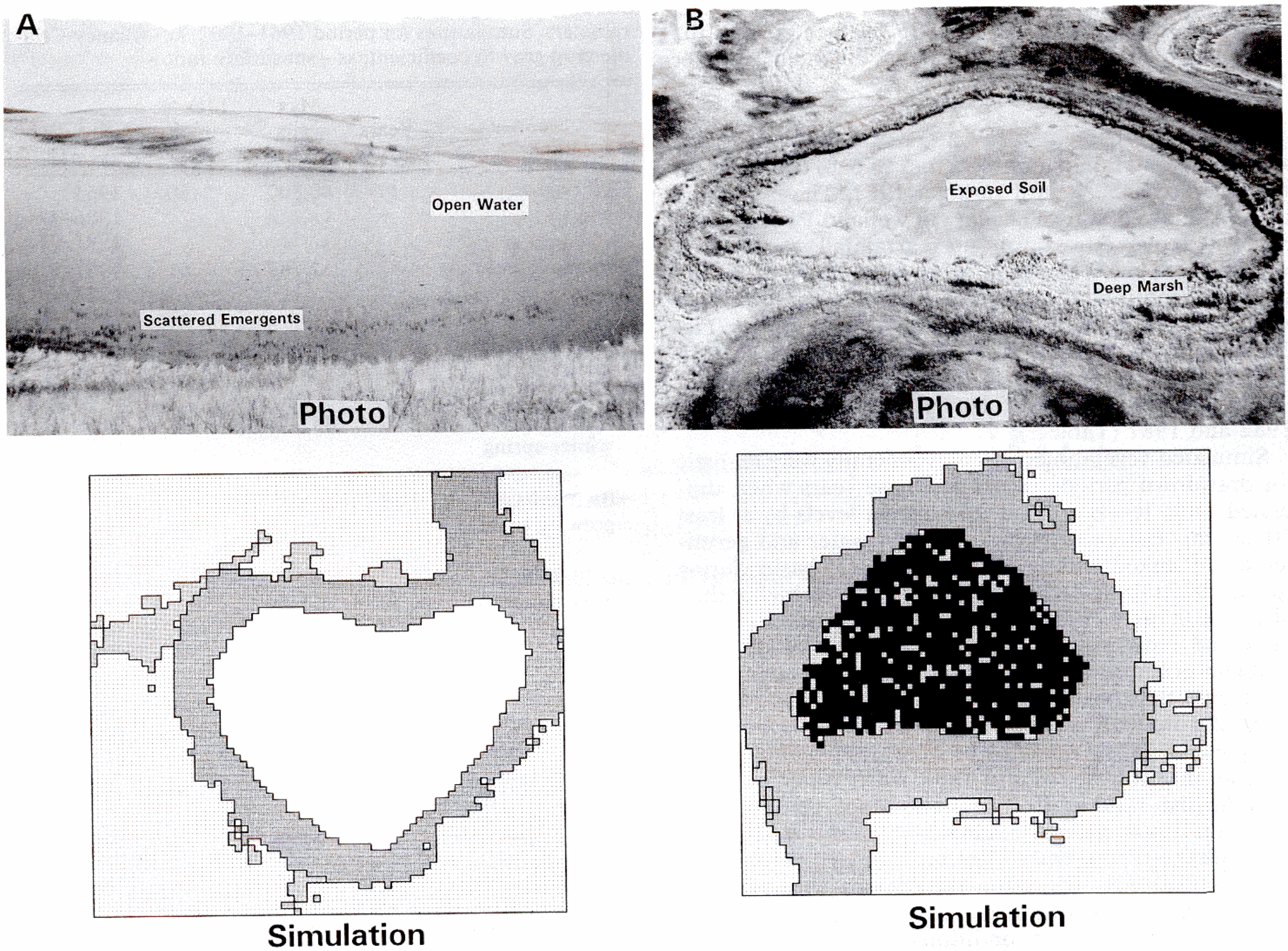


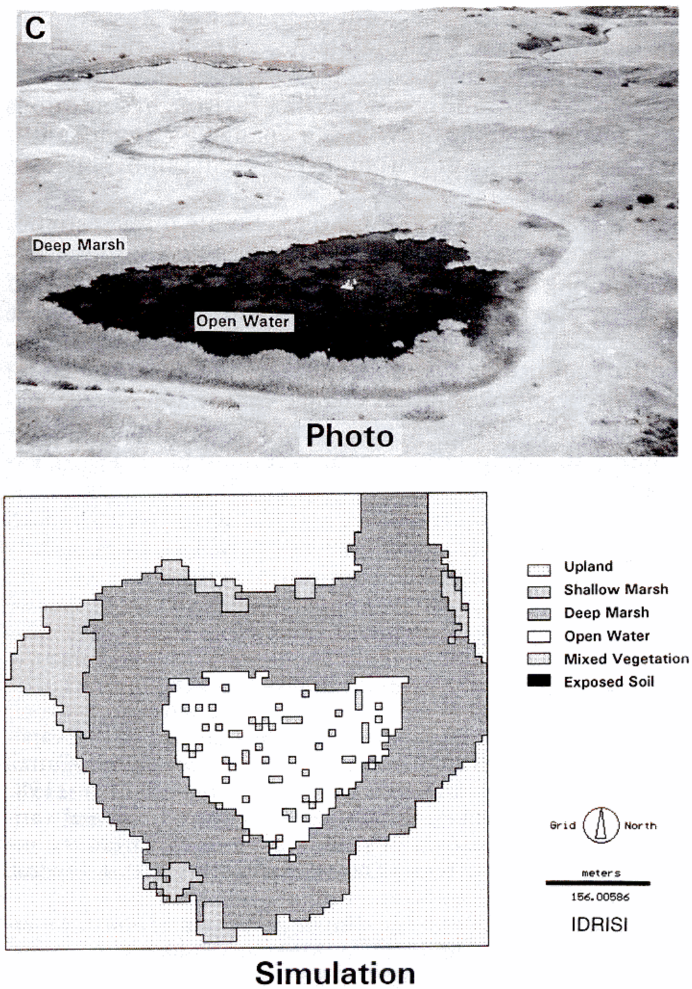
Fig. 5. Vegetation cover and open-water conditions in wetland P1, simulated vs. observed: A—May 1967; B—September 1976; C—July 1984. Photographs by G. Swanson.

Vegetation dynamics in the model were relatively insensitive to subtle changes in hydrology, particularly during wet or average years. Cover ratios among many of the sensitivity simulations were similar despite differences in water level and hydroperiod (maximum percent open water and years with plant growth in the central basin in Table 3). Similarly, a difference in maximum water volume of nearly 5,600 m^3 (when volume was $>39{,}000$ m^3) between the $+0.10$ *kc* winter-spring and the -0.10 *kc* winter-spring produced a difference in maximum open water of only 2% (Table 3). Vegetation dynamics were most sensitive to differences in water level during dry periods when relatively small differences in water level caused more noticeable differences in cover dynamics (Table 3).

Discussion

Model performance—WETSIM 2.0 has several advantages compared to the original model (Poiani and Johnson 1993*a*). Hydrologic calculations were changed from site-specific empirical relationships to more mechanistic-based algorithms. These changes improved submodel performance over original results, particularly during dry periods when simulated water levels had been consistently overestimated (Poiani and Johnson 1993*a*). Also, the vegetation submodel of WETSIM 2.0 more accurately portrayed late-season drawdown, including delayed germination (Harris and Marshall 1963; Welling et al. 1988; Merendino et al. 1990) and occurrence of exposed soil in the central basin.

Model transferability is improved greatly with the elimination of site-specific empirical relationships. Therefore, it is anticipated that WETSIM 2.0 can now be used on semipermanent wetlands in other regions of the Great Plains, such as the Coteau areas of South Dakota and the Prairie Provinces in Canada; however, calibration of several parameters likely will still be necessary. For example, the percent of EPIC-generated subsurface recharge that represents net seepage inflow will differ from site to site depending on hydrogeologic setting (Winter 1989). It may



also be necessary to calibrate boundaries of water-depth categories in the vegetation submodel if dominant emergent species are different than those found in North Dakota. Model application at other sites still will depend on the availability of some data, including general knowledge of subsurface dynamics.

Original, unadjusted water-depth boundaries between cover types in the vegetation submodel (calibrated using 1979–1989 data) produced inaccurate results. Poor knowledge of water levels during the 1960s and 1970s in part may have contributed to inaccurate cover changes in the unadjusted simulation. Lack of continuous observed water-level data for this period precluded testing the vegetation submodel independently of the hydrology submodel. We believe, however, that problems with unadjusted water depth categories primarily illustrated limitations associated with submodel calibration. An 11-yr data record was insufficient because those years did not encompass a full range of climatic conditions and vegetation dynamics, including both changes before and after major wet and dry periods.

Calibration of Blaney-Criddle crop growth coefficients in winter-spring and during the growing season were based on best-fit between model results and observed data. Growing season coefficients needed to be increased (increased potET) from original values recommended for alfalfa to more accurately represent greater water losses from emergent wetland vegetation. This is in agreement with experimental studies on wetland emergent vegetation. Allen et al. (1992) showed that measurements of evapotranspiration from isolated stands of wetland emergent vegetation (i.e. *Typha* and *Scirpus*) using drainage lysimeters were from 60 to 80% greater than for alfalfa reference stands.

In addition, Blaney-Criddle crop coefficients were decreased in winter and spring months (decreased potET) to more accurately represent upland snowpack. Attenuation of winter snowpack was less than expected and may be due to several factors. First, nonsite winter precipitation data may have differed from winter precipitation at the site. Second, simulated snowmelt losses could have been portrayed inaccurately due to the relatively coarse monthly time-step used in the model. Year-to-year snowpack and snowmelt dynamics are the primary factors affecting wetland refill (Woo and Winter 1993) and, as such, need accurate representation in any prairie wetland model.

Simulations illustrated the sensitivity of the model to small changes in growing season evapotranspiration and subsurface flow. Sensitivity of wetland hydrology and vegetation dynamics to growing season evapotranspiration is consistent with hydrologic studies of prairie wetlands (Kadlec 1993). Evapotranspiration is the major water loss in semipermanent prairie wetlands (Shjeflo 1968; Woo and Rowsell 1993) and is expected to change with a changing climate (Martin et al. 1989; Rosenberg et al. 1989; McKenney and Rosenberg 1993). Seepage inflow and outflow, in contrast, vary considerably among prairie wetlands, but even small daily fluxes can be a significant portion of a wetland water budget over an entire season (Shjeflo 1968; Kadlec 1993; Woo and Rowsell 1993). Calibration of subsurface inputs and evapotranspiration was possible in this study because of long-term water level data for wetland P1, and results illustrate the value of such data for developing realistic models. Use of WETSIM 2.0 should be restricted at this time to semipermanent sites dominated by net subsurface inflows or modified to reflect net seepage outflow.

Implications for assessing climate change—The ability of the wetland model to reproduce wet-dry cycles over a three-decade period lends credence to its use in exploring potential effects of climate change (DeAngelis and Cushman 1990). Although the model cannot be used as a predictive tool because of large uncertainties associated with both climate change and ecosystem processes, it can be a valuable heuristic tool used to examine response of semipermanent prairie wetlands to changes in external conditions such as temperature and precipitation.

Testing of the model over the period of record for climate data (1900 onward) is our next step in assessing model performance under the current climate. This period encompasses multiple wet and dry periods including extremely wet conditions in the early 1900s (D. Rosenberry pers. comm.) and widespread drought of the 1930s (Rosenzweig and Hillel 1993). Simulation of water levels in wetland P1 through spring 1995 also is desirable because 1993–1995 was one of the wettest periods on record (LaBaugh et al. 1996).

Several aspects of our results using WETSIM 2.0 have implications for assessing effects of potential climate change on wetland hydrology and vegetation. First, revision from empirical to mechanistic hydrologic components should improve application to climate conditions outside the range for which the model was calibrated, although any such simulations still need to be interpreted cautiously. Second, simulation results indicated that the model produced slightly drier conditions than those observed: one simulated dry period (1981–1982) did not actually occur, and one simulated dry period was drier than that observed (1972–1973). Assessment of wetland water level and cover ratios under a changing climate using the current model version may be biased toward drier conditions and should be considered when viewing results from climate change analyses. Adjustment of wetland model parameters based on the entire three decades could improve model performance and potentially reduce such bias. For example, model performance over the three decades was better with higher-than-calibrated subsurface inflow (i.e. 15.6 vs. 13%).

Third, the hydrology submodel in WETSIM 2.0 had an imposed lower limit for decreases in water elevation. This assumption appeared satisfactory for representing cover and water dynamics for the 32 yr simulated herein, but it may not be adequate under a warmer climate. Water elevation in the central basin may drop well below the ground surface if climatic conditions become effectively drier (Woo and Rowsell 1993). A significant portion of precipitation would then contribute to groundwater recharge rather than to increases in surface-water level. In addition, current subsurface limitations preclude conversion of the central basin to shallow marsh or upland cover types which could occur if water-level decreases with a changing climate are large. Integration of the hydrology submodel with a groundwater model is underway to address these issues.

Finally, long-term observations for wetland P1 show that it may be desirable to incorporate wetland salinity changes during wet and dry cycles (LaBaugh et al. 1996). Changes in salt concentrations, particularly during drawdown, can alter wetland vegetation. In turn, different plant species (e.g. deep vs. shallow marsh species) can influence the length of time a wetland is dominated by emergent cover because of variations in water-depth tolerance, as was demonstrated in P1 in 1977 and 1992. During the drawdown in 1977 salt concentrations increased dramatically and whitetop (*Scolochloa festucacea*), a more salt-tolerant shallow marsh species, dominated the central basin (LaBaugh et al. 1996). In contrast, the prolonged drought of 1988–1992 produced conditions such that salt concentrations were diluted after 1989 and the central basin was dominated by newly germinated hybrid cattail (*Typha glauca*), a deep marsh species (LaBaugh et al. 1996). The prolonged drought caused the water table to drop slightly below the basin and salts were flushed from the drawdown zone as rainfall moved out of the wetland by transpiration-induced seepage (Winter and Rosenberry 1995). Length and characteristics of drought conditions may change significantly with a changing climate and it may become more important to represent salinity changes in the model.

Application of WETSIM 2.0 to climate impact studies can now be performed with a reasonably thorough understanding of model ability and bias. Use of GCM-based and hypothetical scenarios of potential climate change (Sulzman et al. 1995) will enhance understanding of wetland dynamics and will shed light on those aspects of hydrology and vegetation change that may undergo significant shifts with changing climate. Assessment of seasonality of precipitation changes (Poiani et al. 1995), extreme events (Katz and Brown 1992), and asymmetric changes in minimum and nighttime temperatures (Karl et al. 1993; Kukla and Karl 1993) will be particularly important for shallow-basin prairie wetlands.

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